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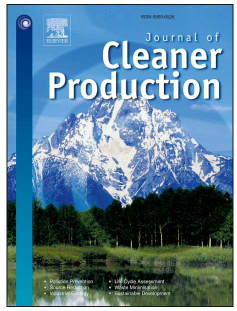

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The incorporation of construction and demolition wastes as recycled mixed aggregates in non-structural concrete precast pieces

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ABSTRACT

Concern for the environment has lately heightened awareness about the need for recycling in the construction industry. However, some standards, such as the Spanish standard, only accept the recycling of aggregates derived from concrete, which limits the extensive use of construction and demolition waste, which are produced in much bigger volumes. The aim of this work was to explore the possibility of using recycled mixed aggregates (RMA) in the preparation of precast non-structural concretes. To that end different percentages of natural aggregate were replaced by RMA in non-structural elements (25, 50, 75 and 100%). Contents of cement, water, and the dosages commonly used by companies were unchanged by the introduction of RMA. The characterization of the prepared elements has been done using the specific tests for each type of non-structural element (terrazzo for indoor use, hollow tiles, kerbstones and paving blocks): compression and flexural strength, water absorption, dimensional tolerances, abrasion and slipping resistance. The paving blocks, kerbstones, and hollow tiles prepared were tested for 360 days. The stability of the tested properties confirmed the possibility of using these wastes on an industrial scale satisfying the standard requirements.

However, the surface of terrazzo with RMA is not as good as that prepared with natural aggregate.

Keywords: Mixed recycled aggregate, non-structural concrete, precast concrete, mechanical properties, water absorption.

1. INTRODUCTION

Recycling and reuse are becoming increasingly necessary in today's world. The construction industry, one of the greatest offenders in terms of pollution, is starting to be concerned about the issue. One of the main environmental problems caused by civil work and building construction is the amount of construction and demolition waste material (C&DW) created every year, which is deposited mainly in dumps. In addition to that, for every new work huge amounts of aggregate are required. A current trend to avoid the accumulation and treatment of waste and to reduce the consumption of natural resources needed to produce the aggregate is the use of recycled aggregates which retain the required properties of concrete. C&DW were used to produce concrete and the mechanical properties, as well as the water absorption were measured at 28 days (Medina et al., 2014), reaching the conclusion that regarding those properties the produced concrete would be apt for housing construction, but no measurment in the long term was taken, and properties may change with time. Mefteh et al., (2013) studied the influence of the moisture in the recycled aggregates determining that using pre-wet or saturated surface-dried aggregates improves the mechanical properties measured at 28 days, but again no measurement is made in the long term. This works deal with laboratory prepared samples also, and no especific use is thought for the prepared concrete samples. Other works determine the mechanical properties after one year (Thomas et al., 2014) but samples are prepared in the laboratory and some factors, such as w:c ratio are changed, fact that could be a problem when trying to manufacture concrete at an industrial scale. The measurement of the evolution of the properties required for the constructive use of the prepared elements is very important, because it shows the tendency, tha in case of being a decreasing tendency will not guarantee the properties in the long term.

Directive 2008/98/CE about wastes (European Parliament, 2008) states the necessity of reducing the use of natural resources and the need for recycling. It predicts that by 2020 70% of the C&DW generated should be reused, recycled and assessed.

By means of processing C&DW, recycled aggregates are obtained. Depending on their original waste material, recycled aggregates could be concrete, ceramic or a mixture (recycled mixed aggregate, RMA). RMA constitutes around 80% of C&DW(Regional government of Madrid, 2012). It comes from building demolitions and contains a wide range of materials, such as concrete waste, pavement material, ceramic products, and, in lower quantity, other materials such as gypsum, glass, wood, etc. A paper recently published (Rodríguez et al., 2015) studies the real situation of the reusing of C&DW in Spain, focused on the work of the recycling plants, and on the role of the Spanish Goverment . One of the conclusions of the work is that the government's role should be more active promoting the reusing of C&DW. Present work is focused to explore the possibility of using these wastes at industrial scale for some constructive elements, and could help to enhance the clean industries.

Efforts have been made on the study of reusing C&DW to obtain different constructive elements. Some studies (Sousa et al., 2003; Yang et al., 2011) have shown that, in elements made of vibro-pressed precast concrete, such as blocks or pavement blocks, the use of concrete recycled aggregates, in fine fraction as well as coarse fraction, the substitition of natural aggregate by RMA up to 50% or 60%, had no strong effect. Other studies have analysed the behaviour of concrete pavements made with ceramic recycled aggregates. It was observed that increasing the percentage of substitution decreases strength, density and abrasion resistance. However, these works show that, up to a substitution percentage of 32.5%, the criteria established by Regulation EN 1338 on pavement blocks are fulfilled (Jankovic et al., 2012).

A comparison has been made between the performance of specimens of non-structural precast concrete for pavements (blocks), some of them with concrete recycled aggregates and others with ceramic recycled aggregates. The results show that with ceramic recycled aggregates density and compressive and tensile strength decrease, and the level of water absorption increases because of the higher absorption of water by ceramic materials used. The substitution of 25% of concrete aggregrates with ceramic recycled aggregates produces pavement which fulfils the Hong Kong regulation on traffic areas (Poon and Chan, 2006).

Soutsos et al. (Soutsos et al., 2011) showed that it is possible to produce concrete for pavement blocks using concrete and ceramic recycled aggregates with similar mechanical properties to those of natural aggregrate, without any need to increase the amount of cement. Even tough some works replicated the industrial procedure in a laboratory (Soutsos et al., 2011), no one of these elements were produced at industrial scale, and the properties were measured at a given age (in general 28 days), leaving the uncertainty of the evolution of the behavior of the properties due to the presence of recycled aggregates.

There are not many studies on the use of RMA in non-structural vibro-pressed precast concrete (López Gayarre et al., 2013; Poon et al., 2009). According to the results obtained in these studies, compressive strength, or resistance, in the case of vibro-pressed elements, decreases whenever the proportion of RMA increases, both for coarse fraction and for fine fraction. The loss of resistance is higher when the water/cement ratio is lower (Chen et al., 2003; Mas et al., 2012b), or if concretes with higher strength are used (Mas et al., 2012a). Regarding the influence of recycled coarse and fine fraction, the addition of fine aggregates causes less loss of strength with low substitution percentages. Nevertheless, for higher substitution percentages, the loss of strength is equal . Other authors (Lovato et al., 2012) have found that a 100% recycled fine fraction substitution causes an 18% decrease in resistance. This decrease is lower with a 100% coarse fraction substitution (24% decrease) , because of the difficulties of compacting when ceramic coarse aggregates are used. The use of fine fraction is also discussed by other authors (Evangelista and de Brito, 2007). However, other studies on recycled concrete with subtitutions of concrete fine recycled agreggate did not obtain satisfactory results (Etxeberria et al., 2007; González-Fonteboa and Martínez-Abella, 2008). Because of these differences, the use of fine fraction in the future should not be dismissed, but more research on it is needed.

The results of flexural strength and tensile strength are contradictory. Some studies state that the addition of RMA causes a reduction of strength (Lovato et al., 2012; Mas et al., 2012a, 2012b), caused by a higher porosity of recycled aggregates and the presence of ceramic materials. Nevertheless, other researchers find that recycled aggregates does not have an important influence on tensile strength (de Brito et al., 2005). They state that their addition improves the tensile strength in relation to the use of conventional concretes, except in the case of 100% substitution (Etxeberria et al., 2007), despite the fact that recycled aggregate is usually more fragile than natural aggregate.

Because of the lower density of recycled aggregates, concretes made with RMA show lower densities than reference concretes. Recycled concrete absorbs more water, as can be expected from the density data. This property increases more if fine recycled aggregates are added than if the replacement is made by coarse recycled aggregates (Lovato et al., 2012; Sousa et al., 2003).

Slipping resistance of recycled concretes presents contradictory results. Yang et al. found that, using recycled aggregates, mainly concrete waste, the slipping resistance improved with increasing substitution percentage (Yang et al., 2011). Conversely, Poon and Lam stated that using recycled aggregates from concrete and glass waste did not change the slipping resistance (Poon and Lam, 2008).

The resistance to abrasion decreases with the percentage of substitution by ceramic recycled aggregate (Jankovic et al., 2012). The use of RMA presents the same tendency: it keeps its values with 20% substitution, and the resistance to abrasion decreases with 40% substitution (Mas et al., 2012b). Some researchers have observed that ceramic aggregate is harder than the rest (Mas et al., 2012b; Poon and Lam, 2008).

This work is focused on the possibility of using a coarse fraction of RMA in the production of elements made of vibro-pressed precast concrete: kerbstones, pavement blocks, terrazzo and hollow tiles. In order to study how RMA affects the properties of these items, different substitution percentages have been used, testing its influence in terms of resistance, bending strength, water absorption, density, abrasion, and slipping resistance. The results seem to be promising as regards the use of mixed recycled aggregates at industrial scale, since all elements were produced in real industries, with their technology and using the dossages provided and employed by the companies; few works cover this essential way to reuse big amounts of C&D wastes. Also, in this work several properties have been measured up to one year after their preparation. The measurements have been made to check the guaranty that these products have for using according to the Spanish and European mandatory Standards. These results guarantee that changes in properties are not important and they still fulfil the required standards, independent of the age of the prepared element.

2. MATERIALS

Two different types of concrete were used, but with similar characteristics. For terrazzo and hollow tiles, CEM II A-LL 42,5 R concrete was used according to the Spanish Standard (AENOR, 2000). On the other hand, for kerbstones and pavement blocks, a CEM I 42.5 R concrete was used. No additive was used in any unit.

As natural aggregate, crushed limestone was used. The aggregates used for terrazzo and hollow tiles were 2/6 mm coarse aggregate and 0/4 mm fine aggregate. For kerbstones and pavement blocks, the coarse aggregate was in the range of 5/12 mm and the fine aggregate in the range of 0/4 mm.

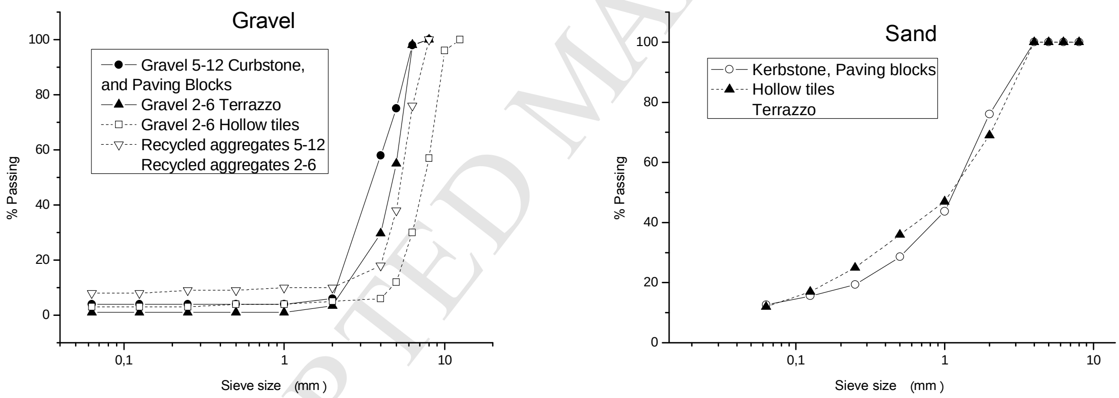

Fig. 1. Granulometric analysis of fractions 0/4, 5/12, 2/6 from natural aggregate and RMA.

The natural aggregates were replaced by recycled mixed aggregate (RMA) in different percentages. Fraction 5/12 mm was used in kerbstones and pavement blocks, whereas fraction 2/6 mm was used in terrazzo and hollow tiles. Fig. 1 shows the granulometric distribution of both RMA fractions, as well as the amount that replaced natural aggregate. It can be observed that fraction 2/6 mm has a higher content in both coarse particles (4-6 mm) and fine particles as compared with natural aggregate and 5/12 mm recycled aggregates show a lower content of particles between 6 and 10 mm as compared with natural aggregate. The use of fine recycled aggregate was ruled out at the beginning of the study. Some studies state that the use of this aggregate increases the water absorption from recycled concrete more than the use of coarse aggregate (Lovato et al., 2012; Sousa et al., 2003). The value of this parameter is limited for kerbstones, pavement blocks and terrazzos (AENOR, 2005, 2004a, 2004b).

Results of RMA characterization tests are shown in Table 1. Comparison of the results with Spanish Standard EHE-08 limitations for concrete recycled aggregates shows that the main properties are not fulfilled by sulphates and fine content. Both aggregate fractions presented a similar composition, as they came from the same C&DW material supply. The composition determination test (Table 2), performed according to UNE EN 933-11, shows that 74.3% of RMA used was made of unbound aggregate or natural stone. The rest, 25.7%, was made of other materials.

Table 1. Results of RMA characterisation.

Test	**5/12 mm**	**2/6 mm**	**EHE-08**
Density (UNE-EN 1097-6)	2.37 g/cm3	2.4 g/cm3	-
Absorption (UNE-EN 1097-6)	4.70%	4.10%	Recycled aggregate + Natural aggregate ≤ 5%
Resistance to fragmentation (UNE EN 1097-2)	29	29	≤40
Flakiness index (UNE EN 933-3)	12	14	<35
Sulphur content (UNE EN 1744-1)	0.18%	0.25%	≤1%
Acid soluble sulphates (UNE EN 1744-1)	0.52%	0.81%	≤0.8%
Water-soluble sulphates (UNE EN 1744-1)	0.22%	0.28%	-
Organic matter content (UNE 103204)	0.31%	0.31%	1%[1]

Fines content (UNE-EN 933-1).	4%	8%	≤1.5%

[1] Coarse aggregate UNE-EN 1744-1

Table 2. RMA components. Fractions 2/6 mm and 5/12 mm.

Test components UNE EN 933-11 (%)	
Floating particles	0.6%
Other	0.5%
Concrete	11.8%
Unbound aggregate	74.3%
Masonry	5.6%
Asphalt	4.9%
Glass	0.1%
Gypsum	2.2%

In addition to the characterisation of fractions 5/12 mm and 2/6 mm, during the year before the tests samples were periodically taken from the Astesa GR waste treatment plant in Cartagena (Spain). The objective was to study the content of certain contaminants (Table 3), such as sulphates or organic substances, which could affect concrete properties negatively.

The content of organic matter causes some problems in the hardening process and loss in terms of resistance values. Results obtained in the samples show low values.

SO_3 content is limited to 0.8% in the EHE-08 standard (Concrete, 2008). This amount corresponds to 1.72% of gypsum in the stoichiometric range. It was observed that all samples presented a lower gypsum content than this maximum accepted value. Nevertheless, some researchers (Mas et al. 2012a), who collected samples for three years (2007 to 2010), found that the main properties which were not fulfilled were water absorption and sulphate content.

Table 3. RMA content.

Test	Standard	Sample 11/06/2010		Sample 08/10/2010			Sample 13/06/2011
		0/3 mm	0/40 mm	0/3 mm	0/40 mm	0/80 mm	0/40 mm
Total amount of soluble salts, including gypsum	NLT 114	1.14%	0.47%	1.78%	0.80%	0.52%	0.02%
Gypsum content	NLT-115/99	1.13%	0.46%	1.41%	0.78%	0.51%	0.02%
Organic matter content	UNE 103204	0.59%	0.15%	0.60%	0.17%	0.19%	0.36%

3. EXPERIMENTAL SET-UP

3.1. Products and dosages

Four different types of elements were prepared: terrazzo for indoor use, kerbstones, pavement blocks and hollow tiles.

Terrazzo tiles were prepared as a two-layer unit measuring 40x40x3.5 cm. Hollow tiles measured 60x25x50 cm. Kerbstones measuring 9x12x25 cm dimensions and 50 cm long were prepared. Lastly, paving blocks measured 20x20x6 cm. Kerbstones and paving blocks were also prepared with the two-layer system.

A 2/6 fraction of RMA was used for terrazzos and hollow tiles. In terrazzos, it was used only in the surface layer, whereas in hollow tiles it was used in the whole unit. A 5/12 fraction of RMA was used for kerbstones and pavement blocks. A layer 23 cm thick was used in kerbstones, whereas a 5 cm layer was used in the case of pavement blocks.

For all products, the initial dosage used was the one commonly used by the manufacturing companies. It was used as a reference dosage and the rest of the dosages were obtained just changing of 25%, 50%, 75% or 100% of the volume of natural aggregate by RMA. An exception was the case of indoor terrazzos, where RMA replacements accounted for only 25%, 50% and 75% of the volume of natural aggregate.

All dosages are displayed in Table 4. The nomenclature used to identify each concrete makes reference to its type: concrete with recycled aggregates (HR), or traditional concrete (HT), which is the non-structural type, kerbstones (KERB), pavement blocks (P), hollow tiles (H) or terrazzo for indoor use (T). Lastly, substitution percentages of RMA are also displayed (0%, 25%, 50%, 75%, or 100%).

Table 4. Dosages used for the preparation of the different elements.

Mixture	***Slump (cm)***	***Cement (kg/m^3)***	***Effective water (kg/m^3)***	***Nat. Agr. 5/12 (%)[1]***	***Nat. Agr. 4/8 (%)[1]***	***Nat. Agr. 0/4 (%)[1]***	***Nat. Agr. 0/3 (%)[1]***	***Rec. Agr. 5/12 (%)[1]***	***Rec. Agr. 4/8 (%)[1]***
HT-KERB-0%	0	360	162	33.00		67.00			
HR-KERB-25%	0	360	162	24.75		67.00		8.25	
HR-KERB-50%	0	360	162	16.50		67.00		16.50	
HR-KERB-75%	0	360	162	8.25		67.00		24.75	
HR-KERB-100%	0	360	162			67.00		33.00	
HT-P-0%	0	360	162	33.00		67.00			
HR-P-25%	0	360	162	24.75		67.00		8.25	
HR-P-50%	0	360	162	16.50		67.00		16.50	
HR-P-75%	0	360	162	8.25		67.00		24.75	
HR-P-100%	0	360	162			67.00		33.00	
HT-H-0%	0	320	120		40.00	60.00			
HR-H-25%	0	320	120		30.00	60.00			10.00
HR-H-50%	0	320	120		20.00	60.00			20.00
HR-H-75%	0	320	120		10.00	60.00			30.00
HR-H-100%	0	320	120			60.00			40.00
HT-T-0%	15	360	276		56.00		44.00		
HR-T-25%	15	360	276		42.00		44.00		14.00
HR-T-50%	15	360	276		28.00		44.00		28.00

HR-T-75%	15	360	276	14.00	44.00	42.00

1 The percentages shown are for the total aggregate.

Dosages were calculated with the same quantity of effective water used in the original dosages from companies. The amount of water was modified according to the difference of the water absorption level between RMA and natural aggregate.

During the production, it was checked that all the mixes had the same slump cone as the reference concrete. Once all the products were made, they were sent directly to the curing concrete areas from companies, where they remained for 28 days before being tested.

Terrazzos are formed by two layers: one from the surface and the one from the base. Both of them are subjected to a process of vibration first and then a process of pressure. To produce the surface layer, a fluid concrete is made (Fig. 2). This concrete is poured into a mould, and later the base surface is added. The base surface is a dry material with a rough finish. The difference of water content level between both layers allows their union. The reason is that the base absorbs the water excess from the surface layer in the processes of pressing and hardening. The aggregate used for the production of the base layer is a 0/3 sand. Fractions used for the surface layer are a 0/3 sand and a 2/6 coarse fraction. As the use of a recycled aggregate fine fraction was ruled out at the beginning of the study, 2/6 RMA was used only in the surface layer.

Fig. 2. Manufacture of terrazzos. Fluid concrete for surface layer.

Fig. 3. Manufacture of kerbstones.

Fig. 4. Manufacture of pavement blocks.

Fig. 5. Manufacture of hollow tiles.

In order to produce kerbstones, pavement blocks and hollow tiles, concrete was subjected to a process of vibration and pressure at the same time, inside some metallic moulds. The manufacture of the materials is shown in Figs. 2, 3, 4 and 5.

3.2. Tests

During the preparation of the elements in every company, tests were made to determine the consistency of concrete according to the UNE EN 12350-2 standard (AENOR, 2009). In the case of indoor floor tiles, samples were taken to determine the compressive strength at 28, 90, 180 and 360 days, according to the UNE EN 12390-3 standard (AENOR, 2001). The objective was to study the effects of the addition of RMA on the strength of the weakest layer of the floor tiles.

Mechanical properties of kerbstones, pavement blocks, terrazzos and hollow tiles were determined by resistance and flexural strength tests at 28, 90, 180 and 360 days, according to the UNE EN 1340 (AENOR, 2004b), UNE EN 1338 (AENOR, 2004a), UNE EN 13748-1 (AENOR, 2005) and UNE EN 15037-2 (AENOR, 2011) standards, respectively.

In addition, tests were made on day 360 in order to determine the water absorption of pavement blocks, kerbstones, terrazzos and hollow tiles according to the UNE EN 1340, UNE EN 13748-1 and UNE EN 1338 standards, respectively (this procedure was also used to determine the absorption of hollow tiles).

Resistance to abrasion and slipping were determined in kerbstones, pavement blocks, and terrazzos at 360 days, following the procedure described in the UNE EN 1340, UNE EN 1338, UNE EN 13748-1 standards, respectively. In the case of kerbstones and pavement blocks, wear resistance (abrasion), as well as slipping resistance, was determined in the inner face where recycled aggregates had been used. The outer surface was not tested since RMA were not used in that part. Concrete density was determined according to the UNE EN 12390-7 standard (AENOR, 2001).

Dimensional tolerances were determined at 28 and 360 days, according to the UNE EN 1340, UNE EN 13748-1 and UNE EN 1338 standards.

Each test was performed on four samples at 28, 90 and 180 days, and on six samples at day 360. The presented results are the mean values of all the measurements.

Lastly, mercury intrusion porosimetry (MIP) was used to analyse porosity and the pore network structure of some of the samples. This technique was only used in concretes used for the terrazzos, in order to explain the differences between the results of the water absorption test and the results for the rest. An AUTOPORE IV porosimeter from Micromeritics was used. It has been widely explained in the literature (Cabeza et al., 2002). Two samples were tested to check the repeatability of the measurement.

4. RESULTS AND DISCUSSION

In this section the main results obtained using all the procedures described before are presented and analysed. In some plots, a discontinuous line appears. It indicates the minimum value required by the UNE EN 1338 and UNE EN 13748-1 standards for pavement blocks and terrazzos for indoor use. In the case of kerbstones, they are classified as Class 2, according to the UNE EN 1340 standard.

4.1. Compressive and flexural strength

The results of resistance for pavement blocks, kerbstones, hollow tiles and terrazzos for indoor use are displayed in Figs. 6-9.

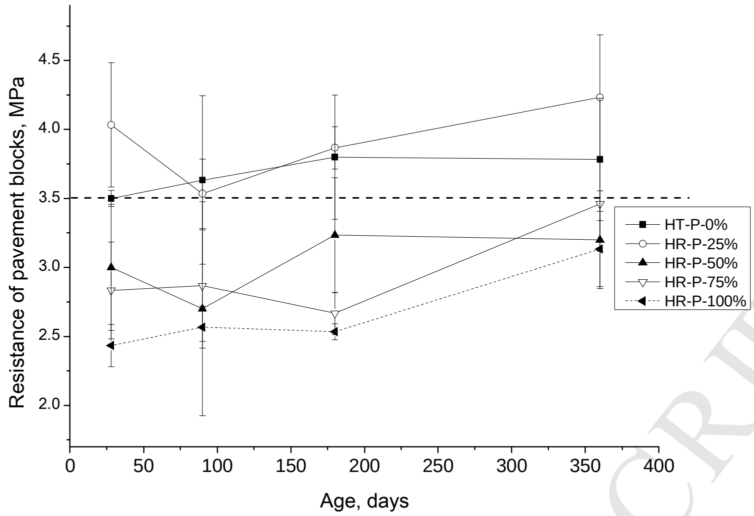

Fig. 6. Time evolution of the resistance of pavement blocks.

As could be expected, the increase of recycled aggregate causes a loss of resistance. However, in the case of pavement blocks and kerbstones, produced with 5/12 coarse fraction, strength decreases only when more than 50% of the aggregate is replaced by RMA.

In the case of pavement blocks, the resistance decreases at day 90 is 25%, 21% and 29.5% for substitutions of 50%, 75% and 100%, respectively (Fig. 6). For a 25% replacement of natural aggregate by RMA, values show an increase of strength at some stages (day 28, 180, and 360). This could be because of a higher percentage of hydrated cement, caused by higher water content. Vibro-compressed concretes usually have very low water content, and a small excess of water could affect the strength positively. As regards pavement block cross-sections (Fig. 10), the higher compaction of the elements, and the lower porosity for HR-P-25% is visible at naked eye.

Minimum values of compressive resistance, required by UNE EN 1338 for pavement blocks (3.5 MPa), are only fulfilled by the reference concrete and the substitution of 25% of RMA. No similar studies were found about the use of mixed recycled aggregates in this context.

The data analysis shows that the loss of flexural strength is, in the case of kerbstones, about 12% for substitutions by RMA of 50% and 75%, and 31.6% for a 100% substitution (Fig. 7).

However, 25% substitution does not cause any loss of resistance. The same was observed in another study (Guzmán, 2010), where substitutions up to 50% of RMA (5/10 fraction) caused loss of resistance below 10%. The main composition of RMA used in that study consisted of: 51% unbound aggregate, 18.5% ceramic materials, 25% concrete. In another study (López Gayarre et al., 2013), 0/12 fraction of RMA (composition: 1.33% asphalt, 17.67% ceramic material, 9.33% concrete, 69% unbound aggregate, 2.67% other components) was used to produce kerbstones. In that study, flexural strength was only affected with RMA substitutions beyond 70%. A loss of 34% in strength with a 100% RMA substitution was observed, which is similar to the value obtained in our study. In another study (Kou et al., 2011), a loss in strength of 35.7% for a 100% substitution of natural aggregates by RMA coarse fraction was seen. RMA composition was 74.6% concrete, 8.6% unbound aggregate, and 16.1% ceramic material.

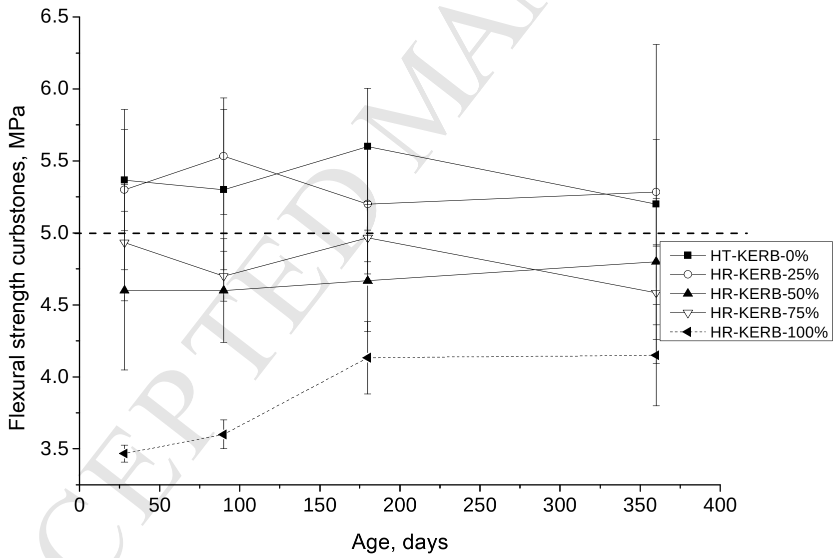

Fig. 7. Results for flexural strength of kerbstones. Time evolution.

The comparison of the obtained results shows that the unbound aggregate is the component of the RMA that has the most positive influence regarding maintaining the mechanical resistance of the elements. Concrete recycled aggregate causes slightly higher losses of strength than the unbound aggregate. The use of ceramic recycled aggregates substituting for concrete recycled aggregates shows losses of strength because of the higher weakness of ceramic aggregates. This result that had been obtained in laboratory tests could be expected.

A recent work also produced paving blocks and kerbstones (and concrete pipes) at industrial scale but only measured the resistance lost at 28 days (Özalp et al., 2016). In that paper authors reach a maximum replacement of 40% of natural aggregate by only coarse, or both coarse and fine recycled aggregates. The nature of the C&DW is not given. Authors report a decrease of 39% of the resistance when using 40% of coarse recycled aggregates, while in this work less than 15% was lost for paving blocks or kerbstones with a 50% of coarse recycled aggregate, and the resistance of the elements with this percentage of C&DW increased slightly with time. The reason might be the nature of the recycled aggregates (high percentage of unbound aggregates) or the compaction method used for the elements produced in this work (vibro-compressed).

Comparing results obtained with limits established in the UNE EN 1340 standard, all concretes produced fulfil Class 1 (minimum resistance 3.5 MPa), and only the reference concrete and the concrete with 25% RMA substitution fulfil Class 2 (minimum resistance 5.0 MPa).

Results obtained for the flexural strength of hollow tiles show reductions, at 90 days, of 14%, 17%, 23% and 36% for 25%, 50%, 75% and 100% substitutions, respectively (Fig. 8). A linear loss of resistance is shown as the proportion of RMA of substitution increases. This has been observed in other studies (Guzmán, 2010; Kou et al., 2012; Leiva et al., 2013; Martínez-Lage et al., 2012; Mas et al., 2012b; Sousa et al., 2003). Sousa et al. (2003) used 2.4/9.6 mm RMA fraction, with a composition consisting of 75% concrete and mortar, 15% bricks, 10% soil. The objective was to produce concrete bricks, and strength losses of about 23% were obtained with RMA substitutions of 40%.

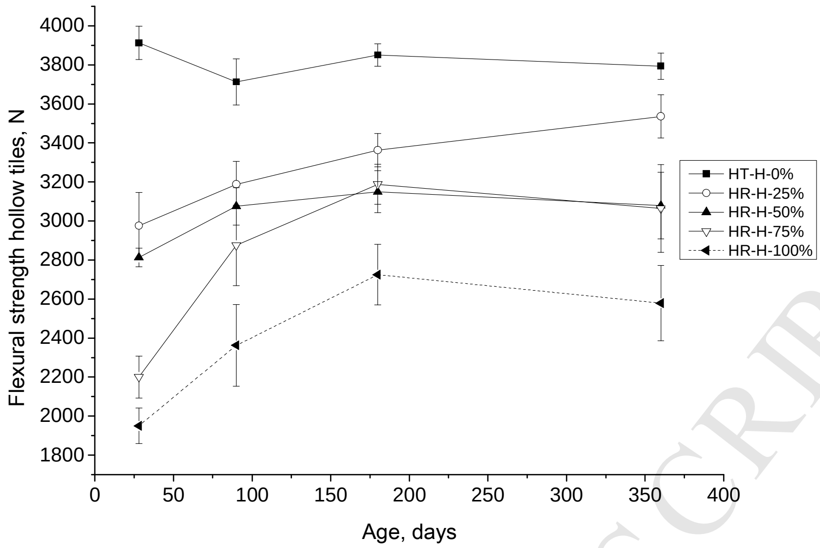

Fig. 8. Results for mechanical resistance in hollow tiles. Time evolution.

According to article 36 of the EHE-08 standard on beam filling elements for floor slabs, light concrete hollow tiles must have a flexural resistance higher than 1.0 kN. This value was reached in this study, regardless of the percentage of RMA used. This result is promising, and it could signal a suitable use for RMA. In another study (López Gayarre et al., 2013), where RMA was also used to produce hollow tiles, the authors concluded that hollow tiles can be obtained by 100% recycled agreggate, since the requirements described in the UNE EN 15037-2 standard are fulfilled.

In terrazzos for indoor use, the flexural strength after 90 days decreased on a percentage of 12%, 14% and 25.5%, for substitution degrees of 25%, 50% and 75%, respectively (Fig. 9).

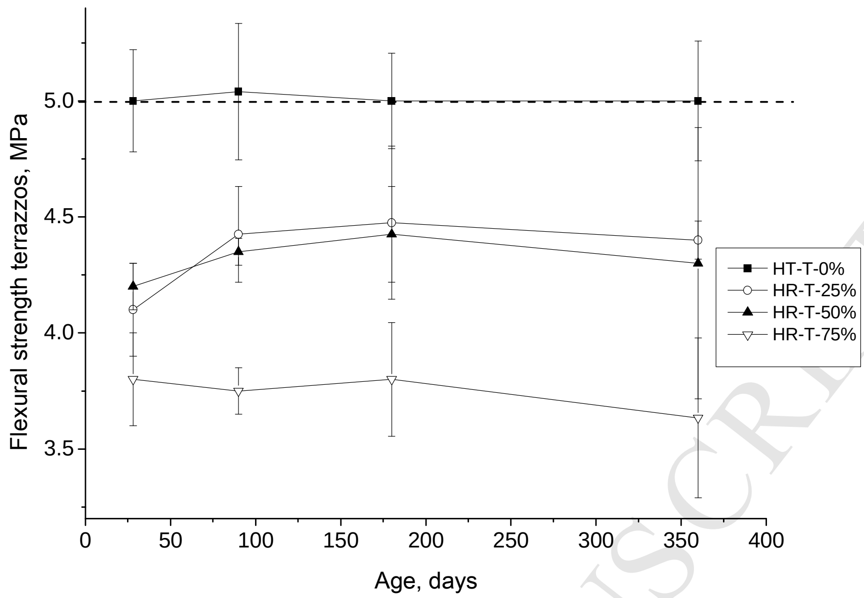

Fig. 9. Results for flexural strength in terrazzos. Time evolution.

Fig. 10. Pavement block cross-sections.

Some samples were also prepared for compressive strength testing, and the results obtained showed a higher resistance loss compared with flexural strength results (Fig. 11). The decrease, in percentage terms, on day 90 was 34%, 35% and 44%, corresponding to the substitution percentages of 25%, 50% and 75%, respectively. These differences among results are justified because the most resistant part of the terrazzos is the base layer, which is formed by dry concrete. Thus, the surface layer, made with fluid concrete and where RMA were used, has less influence on flexural strength in terrazzos.

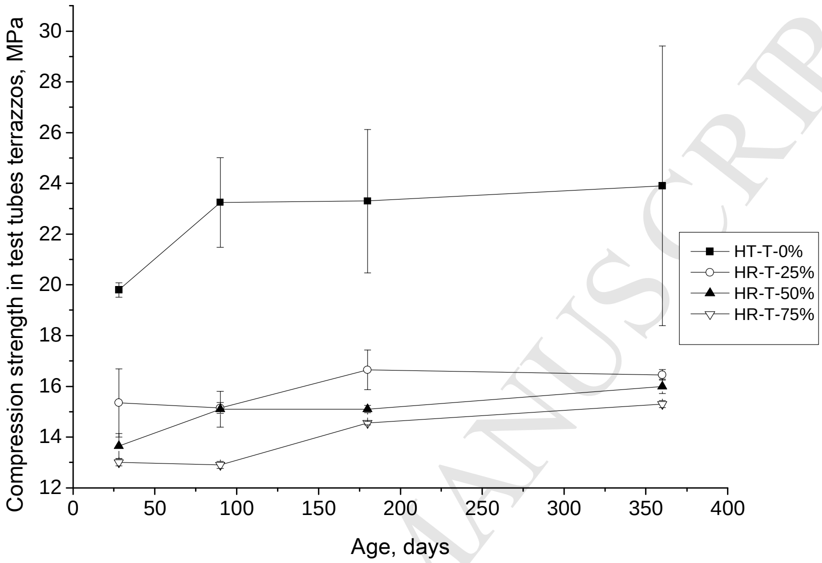

Fig. 11. Results for compression strength in terrazzo samples. Time evolution.

If the evolution of strengths for different precast elements is analysed, it can be observed that decrease of strength caused by the use of RMA is higher after 28 than after 360 days, for substitution percentages of 75% and 100%, in the case of pavement blocks. In kerbstones, the compressive resistance decreases more after 28 days than after day 360 for RMA substitutions of 25%, 50% and 100%. The same result is observed for all substitution percentages in the case of hollow tiles and terrazzos, with the exception of substitution of 75% in terrazzos. This confirms that the acquisition of strength is slower if RMA is used. This phenomenon was observed by other authors (Mas et al., 2012a, 2012b). As regards the fine content of recycled fractions of 2/6 (hollow tiles and terrazzos) and 5/12 mm (pavement blocks and kerbstones), the 2/6 mm fraction has a content of fines 4% higher than the 5/12 mm fraction (8% against 4%). According to the results obtained by Mas et al. (2012b), the evolution of strength of concrete produced with RMA fine fractions is slower, because it could retain some non-hydrated cement mixed with fine. The same result was reported in Evangelista and de Brito (Evangelista and de Brito, 2007), where concrete recycled fine aggregates were used, and it was observed that the mixtures with substitution percentages of 30 and 100% showed increasing resistance after 28 days, whereas the reference concrete stabilised the value of the resistance. In another study (Kou et al., 2011), where concrete recycled aggregates were mainly used, increases in compressive strength and tensile strength after five years were higher for recycled aggregate concretes than for natural aggregate concretes. According to the authors, recycled aggregate from concrete enhances the microstructure of the aggregate-mortar joint area. This effect has been recently reported by studying the microstructure of concrete produced using C&DW (Bravo et al, 2016). The work shows the influence of the nature of the recycled aggregate on the microstructure, and the water absorption of concretes, and in the case of using fine aggregates. On the other hand, coarse aggregates can, during the mixing process, absorb water. It is well known that the self-curing mechanism in concrete has some relation with the absorption and gradual liberation of water (Dhir et al., 1998; El-Dieb, 2007), the hydration level increases. It is possible that the excess of water absorbed by the recycled aggregate included in the mix was released gradually. This would increase the amount of hydrated cement, and, therefore, allow concrete to have a slower gradual acquisition of mechanical resistance. Both hypotheses are possible but it is difficult, given the present results, to decide which is the more accurate. The determination of the mechanism that causes this resistance increase should be studied with other techniques and was not an objective of this study.

Once all the mechanical resistance have been analysed, it is possible to say that using C&DW with higher quantity of unbound aggregates can be used at industrial scale, and no important loose of resistance will happen in most elements excepting terrazzo until one year. The result is very promising because it opens the field of the massive used (industrial scale) of C&DW in non-structural elements with all the guaranties during time.

4.2. Water absorption

In Fig. 12, results of water absorption obtained after 360 days are presented. According to the figure, water absorption in recycled concrete increases with substitution percentage of RMA. An increase of 10%, 16.5%, 14% and 27% was measured for substitutions of 25%, 50%, 75% and 100%, respectively and in the case of pavement blocks.

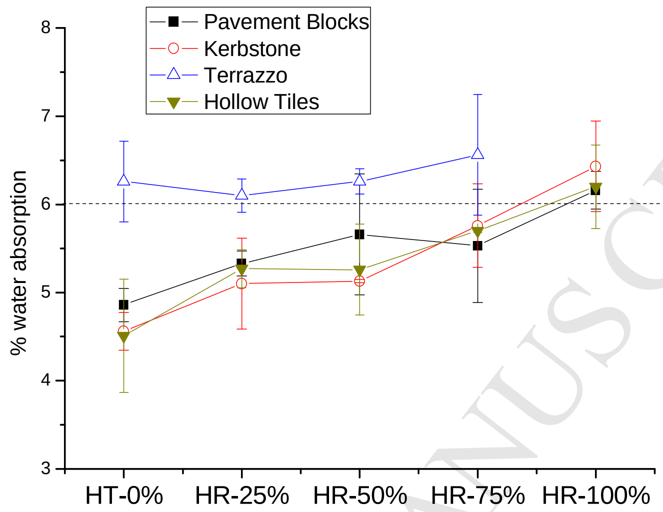

Fig. 12. Results for water absorption in pavement blocks, kerbstones, terrazzos for indoor use and hollow tiles.

Water absorption in such precast elements is related to their climatic resistance. According to the UNE EN 1338 standard for pavement blocks, all concretes can be tagged as number 2 ((≤6% water absorption), except for those that contain 100% of recycled aggregate that should be tagged as number 1. It has to be pointed out that the requirement of some climatic resistance for pavement blocks depends on the country where the standard is used.

In kerbstones, a higher increase is produced for substitutions which are above 50%. Results show an increase of 12%, 12.5%, 26% and 41% for substitution percentages of 25%, 50%, 75% and 100%, respectively.

These results are concordant with the ones obtained by Guzman et al. (Guzmán, 2010). They worked with an RMA 5/10 fraction (RMA main composition: 51% natural or unbound aggregate, 18.5% ceramic materials and 25% concrete aggregate) to produce kerbstones with substitution percentages of about 30% and 50%. Results obtained were very similar, with an increase of about 15% of water absorption for both substitution percentages. Medina et al. (Medina et al., 2014) obtained similar results. The use of RMA (RMA main composition: 28% natural or unbound aggregate, 5.30% ceramic materials, 19.33 asphalt material and 45.64% concrete aggregate) in concretes at the replacement ratio of 50% resulted in sorptivity of the recycled concretes being 10 to 20% higher than the reference concrete. Sousa et al. (2003) reached the same conclusion, using a RMA 2.4/9.6 fraction with a composition consisting of 75% mortar and concrete, 15% ceramic materials and 10% soil. They obtained an increase of 15% of water absorption for 40% substitution percentages. In this study a fine RMA 0/2.4 fraction was also used. It increased water absorption considerably, reaching values twice as large as the ones taken as reference, for RMA substitution percentages of 60% and 70%.

The UNE EN 1340 standard for kerbstones makes the same classification as the one for pavement blocks. Therefore, kerbstones with substitution percentages of 25%, 50% and 75% can be tagged as number 2 (≤6%). In another study (López Gayarre et al., 2013), when the substitution percentage of RMA was above 50%, values of water absorption were higher than the established values of the EN 1340 standard for kerbstones (tagged as number 2).

The results on hollow tiles tests showed an increase of water absorption of 16%, 17%, 26% and 37.5% for substitution percentages of 25%, 50%, 75% and 100%, respectively (Fig. 12).

Results for terrazzos show a different behavior from the rest of the precast elements. The increase of water absorption in terrazzos is only noticeable in substitution percentages higher than 75%. In order to analyse the reason for these results, porosimetry measurements were made of samples obtained from the layer of terrazzos prepared with RMA. The surface layer was analysed, as it is the one that can absorb water. In this case, it was also the surface layer that contained RMA (Fig. 13).

The obtained results are coherent with water absorption results. It can be observed that concretes produced with 25% of RMA have lower total porosity and a higher amount of pores of smaller size. Reference concretes and 50% RMA concretes present a higher quantity of pores of a larger size. There is a peak in pores whose diameter is around 1000 nm, which was not found in the porosimetry of concrete with 25% RMA. Concretes with RMA substitution percentages of 75% clearly show a higher number of larger pores.

The difference among terrazzos and the rest of the precast elements, where an increase of water absorption was observed with increasing RMA substitution, could be caused by better compression (during production) and higher fluxing in the case of 25% RMA. A decrease in the number of pores with diameters between 300 and 2000 nm, approximately, if HR-T-25% is compared with the reference one (HT-T-0), can be seen. This could be caused by a small excess of water, which facilitated the development of a more compact microstructure, as indicated by the slightly lower total porosity.

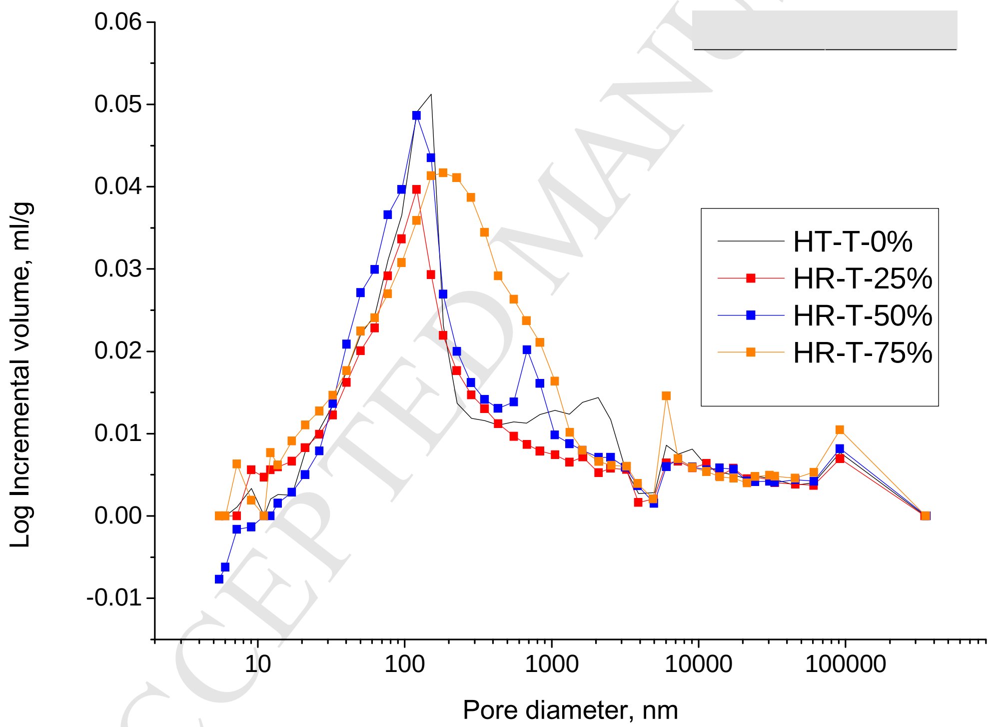

Fig. 13. Mercury porosimetry: terrazzos. Surface layer with RMA.

Lastly, if UNE EN 13748-1 is revised, the maximum absorption from terrazzos must be 8%. This value is fulfilled for every substitution percentage of recycled aggregate (Fig. 12).

4.3 Abrasive resistance

Abrasive resistance of pavement blocks and kerbstones is similar to the resistance of reference concretes up to substitution percentages of 75%. Resistance to the abrasion decreases for substitution percentages of 100% (Table 5). However, no change in this parameter for any substitution percentage in the case of terrazzos was observed. Other researchers found that the use of RMA modifies abrasive resistance with substitution percentages above 40% (Mas et al. 2012b).

Low abrasion resistance in kerbstones and pavement blocks is justified: this test was made in their base layer, because it was the one with RMA.

Table 5. Density, slipping resistance and abrasive resistance after 360 days

Mixture	***Density*** ***g/cm^3***	***Slipping resistance***	***Abrasive wear*** ***mm***
HT-KERB-0%	2.30	82	30
HR- KERB-25%	2.28	71	30
HR- KERB-50%	2.24	64	31
HR- KERB-75%	2.21	70	31.5
HR- KERB-100%	2.13	75	36.5
HT-P-0%	2.15	91	29
HR-P-25%	2.15	95	26
HR-P-50%	-	87	31.5
HR-P-75%	2.02	94	34
HR-P-100%	2.01	89	33
HT-H-0%	2.25	-	-
HR-H-25%	1.96	-	-
HR-H-50%	2.01	-	-
HR-H-75%	1.90	-	-
HR-H-100%	1.93	-	-

HT-T-0%	2.26	110	19
HR-T-25%	2.32	96	17
HR-T-50%	2.31	101	21.5
HR-T-75%	2.29	99	17

4.4 Slipping resistance

Slipping resistance of recycled concretes does not present significant differences in relation to reference concretes in kerbstones, pavement blocks, hollow tiles and terrazzos. Therefore, recycled aggregates seem to have no influence on this property (Table 5). The same conclusions were drawn in another study (Poon and Lam, 2008), although in that case recycled aggregates from concrete and glass waste were used. In another study, where recycled aggregates from concrete waste were mainly used, slipping resistance improved with substitution percentage (Yang et al., 2011).

4.5 Density

Because of the lower density of RMA in comparison with natural limestone aggregates used in the study, density from kerbstones, pavement blocks and hollow tiles is reduced with the use of recycled aggregate. This was observed in other studies (Bravo et al., 2015; Jankovic et al., 2012). Nevertheless, density in terrazzos is similar for every concrete produced (Table 5).

4.6 Dimensional tolerances

Although results obtained for terrazzos are promising, the use of RMA in the surface layer presents a very significant issue because of the high percentage of defects which produce weak zones in the surface layer. The surface in RMA terrazzos is not as good as the surface of terrazzos with natural aggregate. It would be interesting to study its incorporation in the base layer. However, a coarse fraction of aggregate, which has not been used yet, would be needed in order to accomplish it.

In general, the results obtained are promising, and they show that non-structural precast concrete wall units, such as pavement blocks, kerbstones and hollow tiles, can be made by adding RMA and using the same techniques and procedures as the ones used with these kinds of products. In kerbstones, pavement blocks and terrazzos, dimensional tolerances were fulfilled on days 28 and 360. After day 360, no superficial cracks appeared. This aspect is essential, since elements produced at industrial scale seem to have good properties even after one year. This means that RMA could be introduced in the industry, being able to guarantee the performance of the elements.

5. CONCLUSIONS

The following conclusions can be drawn from this experimental study:

- RMA presents higher water absorption than natural aggregates. This influences the production methodologies, the water absorption in produced concretes and the mechanical resistance.
- Essential properties of pavement blocks, kerbstones and hollow tiles are retained until an RMA substitution percentage of 25% is reached. The surface of terrazzos with RMA is not as good as the surface of natural aggregates.
- Generally, the increase of recycled aggregate ratio causes a decrease of mechanical resistance for both 2/6 and 5/12 fractions.
- These losses of resistance because of the use of RMA are higher at day 28 than day 360 for most of the substitution percentages. This confirms that acquisition of resistance is slower with the addition of RMA. This is possibly because of the presence of non-hydrated cement mixed with RMA fine aggregates. Another hypothesis is that a self-curing effect could be produced because of the initial water absorption that recycled aggregates commonly suffer.
- Water absorption in recycled concretes increases with the RMA substitution percentage. In terrazzos for indoor use, the increase of water absorption is only appreciable with substitutions of about 75%.

- Slipping resistance of recycled concretes does not present considerable differences in relation to slipping resistance of reference concretes.
- Abrasion resistance in the case of kerbstones and pavement blocks (recycled 5/12 fraction) presents the same values in relation to abrasion resistance in reference concretes with substitution percentages of up to 75%. Nevertheless, in terrazzos where 2/6 fraction is used, no significant resistance reduction for any substitution percentage was observed.

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